Speleogenetic evolution of the Toirano cave system (Liguria, northern Italy)

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Abstract

The Toirano karst system comprises different caves between altitudes of 340 m and 186 m asl. A detailed investigation of cave pattern, morphologies and of the sedimentary deposits attributes the origin of the caves to rising waters that followed the main vertical structural pathways. Many walls and roofs are sculpted with rising features (cupola and megacusps); in other areas, despite the presence of copious speleothem deposits, vertical feeders that brought the rising waters into the cave system have been localised. A series of geochronological analyses, including several U/Th dating and one cosmogenic burial date, alongside stable isotope and fluid inclusion analyses on some speleothems, have allowed to estimate the age of the highest lying cave (Ulivo) at 2.4 ± 0.40 and the lowest (Bàsura) at 1.45 ± 0.35 Ma ago. Many U/Th dates on speleothems have given ages beyond the limits of the method (>600 ka), confirming the system to be rather old. The stable isotope analyses indicate that the rising water was not peculiarly warm, with T values probably close to the current low-thermal spring in Toirano village, i.e. around 22-23 °C. The hypogenic evidences of the Toirano cave complex have been masked and modified by recent vadose infiltration, but especially by condensation-corrosion processes. Only a detailed multidisciplinary research has allowed to unravel the complex speleogenetic history of this cave system. The hypogenic origin of many ancient caves is probably hard to prove because of these late-stage processes, which erase the most obvious evidences, or hide the typical hypogene features.

1. Introduction

Most caves are epigene in origin, carved by infiltrating surface waters and often arranged in levels, which register the former base level stillstands (PALMER, 1987), helping in unravelling the landscape evolution of the areas in which they were carved. The common epigenic origin is usually supported by the current presence of infiltration waters in caves, the "rounded" tunnels interpreted as phreatic conduits, and the presence of typical evidences of fast-running water (e.g., scallops, fluvial sediments). The geomorphological and depositional evidences of early speleogenetical phases can be partially lost because of weathering, speleothem deposition, late-stage sedimentation, collapses, human activity, etc. There are also processes such as condensation-corrosion, boosted by the presence of guano and/or warm and moist air circulation in caves, which are greatly underestimated in the shaping of caves (CAILHOL *et al.*, 2019). These processes can be extremely important in the late speleogenetic stages, especially when cave passages become opened to the surface, erasing evidences of older events. Accordingly, the study of cave formation needs an accurate interpretation of underground morphologies and bedrock features, supported by geochemical and stratigraphic analyses of cave deposits, and the knowledge of geology of the area and surface dynamics related to climate and landscape evolution (AUDRA & PALMER, 2016; COLUMBU *et al.*, 2015, 2017; BALLESTEROS *et al.*, 2019; BELLA *et al.,* 2019). The Toirano karst system displays multiple cave levels and an impressive variety of underground morphologies, as much as probably making it the Italian show cave with the highest geodiversity. In-detail investigation of cave morphologies and stratigraphy, U-Th dating, stable isotope and fluid inclusion analyses of speleothems and cosmogenic burial dating of sediments, aimed at providing information on the evolution of this complex cave system in a changing climate, environment and landscape.

2. Study area and methods

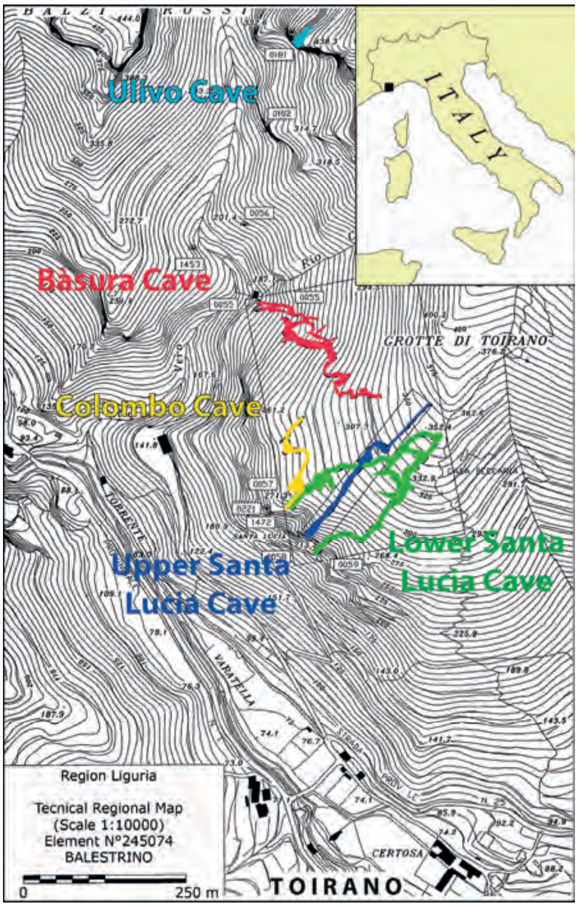

Figure 1: Study area displaying caves location. The thermal spring is placed some hundred metres south of the Certosa (just outside of this map) (Gruppo Speleologico Cycnus & Delegazione Speleologica Ligure, 2001).

The Toirano karst system develops along the lower slopes of Mt. Carmo di Loano (1389 m asl), half a kilometre north of the small village of the same name (Savona Province, Liguria, north-western Italy) (Figure 1).

The caves open at various altitudes along the slopes on the hydrographic left of the Varatella torrent, only 4.5 km away from the coast. They are carved in the lower calcareous part of the *San Pietro dei Monti Dolostones* (Middle Triassic). Toward the south, the carbonate rocks are interrupted by an important regional NE-SW fault with a vertical offset of at least 200 m, along which the thermal spring of Toirano is located (70 m asl). This spring (ca. 100 L/s) delivers slightly basic waters of 22-23 °C (ca. 600 µS/cm at 20 °C, hardness of 23 °F, 25-37 mg/L $[SO_4^{2-}]$) (CAVALLO, 1990; CALANDRI, 2001).

Climate in Toirano is mild Mediterranean and maritime, warm and temperate, with an average annual temperature of 14.3 °C (from a mean of 6.6 °C in January to 22.6 °C in July); annual rainfall is 830 mm with no pronounced wet season, whilst June and August are essentially dry. The caves of Toirano are known at least since the XV century and archaeological digging has shown they have been used by ancient human groups at least starting from the Lower Paleolithic (around 150 ka) (AROBBA *et al.*, 2008). Bàsura Cave became famous in the 50s when footprints of the Upper Paleolithic Man (12,000 years BP) were discovered. It is now connected with the Lower Santa Lucia Cave by an artificial tunnel, and equipped for tourist visits.

Toirano and its caves have been visited several times between 2015 and 2019 to carry out geomorphological observations in all passages. During these visits, sediments, speleothems (pieces found broken along the trails) and secondary minerals have been sampled in most of caves.

Minerals have been analysed with classical techniques (Diffractometry, Scanning electron microprobe analyses) at Genova University and at CINaM (CNRS and Aix-Marseille University). Some samples of quartz- and feldspar-containing sands have been sampled for Al-Be cosmogenic burial dating at the CEREGE-CNRS (Aix-Marseille University). Fragments of speleothems have been dated by the U-series method at the University of Taiwan, whereas stable isotopes were measured at the University of Cambridge (UK) and Almeria (Spain). A double-polished thin section has also been prepared to study a thick cm-sized calcite raft from Bàsura Cave for fluid inclusion petrography.

3. Results and discussion

A series of important speleogenetic indicators have allowed to reconstruct the evolution of the cave system (Fig. 2).

1. The caves develop along clearly distinguishable levels asl: Ulivo (340 m), Colombo (250 m), Upper Santa Lucia (215 m), Lower Santa Lucia (210-205-200 m), and Bàsura (185-175-165 m), respectively. These levels testify relative long-lasting stable phases in which the local base level and caves were at the same altitude.

2. Morphologies related to fast and turbulent flow (scallops) have not been detected. Clastic sediments are scarce, and range from coarse pebbles to gravels, sands and clays. Apart from angular clasts located in entrance areas (especially Bàsura), allogenic fluvial fine gravels are found only up to 100-200 metres into the caves, with an inward fining trend. These sediments were clearly introduced from outside, and in certain cases appear to have completely filled existing caves (e.g., Colombo Cave).

3. The caves are essentially characterised by morphologies of slowly flowing ascending fluids (rising channels, superposed cupola). Some rising conduits are almost certainly feeders. Except from limited seepage spots, no trace of significant active or inactive epigenic recharge, such as vadose shafts and meanders, have been detected.

4. The active thermal and slightly sulphidic spring in the village of Toirano, only 500 m south of the caves and ~100 m below the Bàsura Cave, indicates ongoing processes of deep fluid circulation today. Analogously, deep fluid circulation might have been active in the past.
5. No typical weathering by-products of sulphuric acid speleogenesis such as alunite and jarosite are present. The following minerals were detected: calcite, aragonite, huntite, and magnesite (minerals typical in dolostone-hosted caves), gypsum, ardealite, brushite, F- and OH-apatite, Leucophosphite/spheniscidite, and newberyite on the old guano deposits.

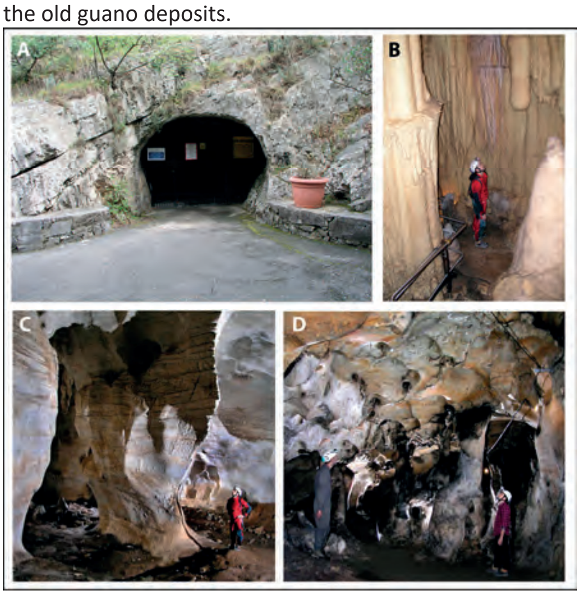

Figure 2: A. Entrance of Bàsura Cave (note stratification and the rounded cross-section); B. Poolfingers in the Cibele area, Bàsura Cave (note welt on the left with calcite rafts); C. The rock pillar isolated by condensation corrosion in Colombo Cave; D. Ceiling cupolas in the final part of Upper Santa Lucia Cave. All photos by Jean-Yves Bigot.

6. The cave-forming fluids were probably rich in CO_2, and might have been slightly thermal, whereas sulphate (and sulphuric acid), given the presence of the slightly sulphidic spring today, played only a very minor role (if at all).
7. Stable isotope analyses have pointed to paleo-temperatures in average of 13-14 °C confirmed also by the fluid inclusion observations on one sample of calcite raft. The $\delta^{13}C$ values (between -8 and -11‰) are consistent with a contribution from above lying soils, confirmed also by the $\delta^{18}O$ values which are typical of low temperature calcites precipitating from mid-latitude rain waters.
8. Most of the calcite speleothems (also in the lowest and youngest cave levels) reported ages beyond the U-Th method limit (ca. 600,000 years), older than 615 ka (POZZI *et al.*, 2019) and even 780 ka (reversed magnetic signal, BAHAIN, 1993), suggesting that the entire karst system is certainly older than 780 ka.
9. The allogenic sands sampled in Colombo Cave have delivered a burial age of approximatively 1.85 ± 0.35 Ma, which represents the minimum possible age of the voids these sands fill. This age and the mean global sea level during the Gelasian (-100/+10 m respect to today's sea level) allows to estimate a maximum uplift rate of 0.16 ± 0.03 mm/y, giving a rough idea of the age of all cave levels: Ulivo Cave (2.4 ± 0.4 Ma), Colombo Cave (1.85 ± 0.35 Ma), Upper Santa Lucia Cave (1.65 ± 0.35 Ma), Lower Santa Lucia (1.55 ± 0.35 Ma), and Bàsura Cave (1.45 ± 0.35 Ma).
10. Intense signs of condensation-corrosion are visible in the inner parts of the caves, where the cave atmosphere is close to moisture saturation. Warm moisture condenses on the cooler ceiling and the descending water film evaporates along the walls and floor. These processes probably started when low-thermal water was still present at depth, or at least the rock mass was still heated by the thermal fluids, producing rising warm and moist air flows.
11. Condensation-corrosion is particularly evident in the large passages of the entrance areas in Colombo, in both Upper and Lower Santa Lucia, and in Bàsura caves, which openings are located on a southwest facing cliff, where warm and wet air masses from the sea frequently rise along the valley. Cave voids significantly expanded by condensation-corrosion, probably for several metres, cancelling most of the original features and sediments.
12. The condensation-corrosion process is also boosted by bat colonies, which abundant presence in the past is testified by the large old guano mounds and phosphate minerals. Guano decay is an exothermic process releasing both water vapour and carbon dioxide, thus enhancing condensation above the guano heaps, and high CO_2 levels in the air. Other acids released by guano decay make the atmosphere particularly aggressive and corrosive (CAILHOL *et al.*, 2019). Based on our observations in Colombo Cave, the wall retreat by biocorrosion processes alone can here be estimated in at least 1 m on both sides of the passage, probably double on the roof.

4. Conclusions

On the basis of the geomorphological observations, geochemical analyses and U/Th dating, the Toirano caves formed by the action of rising hypogenic fluids that followed deeply-rooted subvertical fractures. In the lower passages (Bàsura and Lower Santa Lucia caves), the traces of ascending fluids are still well visible in many areas, with rising channels and superimposed cupolas.
Based on our data, the following speleogenetic scheme can be presented based on the burial date obtained in Colombo Cave:

A) The cave started forming at the water table level fed by a deep-rooted fracture, with thermal (possibly H_2S-rich) waters carving the cave in both phreatic, but mainly aerate conditions;
B) A marine ingression during the final phases of the Lower Pleistocene (Gelasian, ca. 2.6-1.8 Ma) caused the river valleys to aggrade, and the entrance parts of the cave were completely filled with gravels and sands (pockets on the roof of the cave are still filled with remnants of these sediments, whose burial age is around 1.85 ± 0.35 Ma);

C) successive Pleistocene mountain uplift caused the Varatella torrent to entrench, partially emptying the cave which, at least in the early stages, was probably still actively enlarging by rising hypogene fluids. The continuous uplift caused the intersection of the water table with the feeding fractures to shift laterally and to lower lying elevations, causing the formation of the lower levels of the cave system;
D) in the final stages hypogenic waters abandoned the cave system: since then, the large cave entrances are subject to air circulation, bat roosting and frequentation, and condensation-corrosion processes started to remove most remnants of the older sediments and speleothems (several of which overcome the U/Th dating limit, i.e. > 600 ka). The lowest cave level, corresponding to Bàsura Cave, is certainly older than 780 ka, and might be older than 1 million years.
E) The intense condensation-corrosion, still very active today, has erased many of the morphologies and deposits of the original hypogenic speleogenetic phase. Ancient guano deposits appear to have a strong influence on later vadose condensation-corrosion processes, playing an important role in shaping the voids they occupy. Wall retreat by sole condensation-corrosion can be estimated in over 1 metre in the highest caves (Colombo) because of their large entrance size, exposure to moving external air mass directions, and past presence of large bat colonies.

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